AD-A153 550   ATMOSPHERIC PROBING BY ACTIVE MILLIMETER WAVE SYSTEM   1/1
                (U) ROSENSTIEL SCHOOL OF MARINE AND ATMOSPHERIC SCIENCE
                MIAMI FL   R LHERMITTE MAR 85 ARO-18627.2-GS
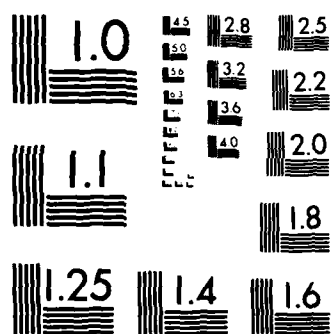UNCLASSIFIED   DAAG29-82-K-0082   F/G 17/9   NL

END
FILMED

DTIC

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS
BEFORE COMPLETING FORM

1 REPORT NUMBER	2. GOVT ACCESSION NO.	3 RECIPIENT'S CATALOG NUMBER
ARO 18627.2-GS	N/A	N/A

4. TITLE (and Subtitle)

Atmospheric Probing by Active Millimeter
Wave System

5 TYPE OF REPORT & PERIOD COVERED

Final
15 Mar 82 – 14 Jul 84

6 PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)

Dr. Roger Lhermitte

8. CONTRACT OR GRANT NUMBER(s)

DAAG29-82-K-0082

9. PERFORMING ORGANIZATION NAME AND ADDRESS
University of Miami, Rosenstiel School of Marine
& Atmospheric Science, MPO
4600 Rickenbacker Cswy., Miami, FL 33149

10. PROGRAM ELEMENT. PROJECT, TASK
AREA & WORK UNIT NUMBERS

11. CONTROLLING OFFICE NAME AND ADDRESS

U. S. Army Research Office
Post Office Box 12211
Research Triangle Park, NC 27709

12. REPORT DATE
March 1985

13. NUMBER OF PAGES
13

14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)

15. SECURITY CLASS. (of this report)

Unclassified

15a. DECLASSIFICATION/DOWNGRADING
SCHEDULE

16 DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

NA

18. SUPPLEMENTARY NOTES

The view, opinions, and/or findings contained in this report are
those of the author(s) and should not be construed as an official
Department of the Army position, policy, or decision, unless so
designated by other documentation.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Millimeter Wave Radar, Doppler Radar, Cloud Physics

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The objectives of the contract are to design, assemble, and test a
W-band Doppler radar operating at a frequency of 94 GHZ (λ = 3.3 mm).
The ultimate goal of the project is to use the radar in a cloud physics
research program. The radar design is based on an MTI scheme in which
the transmitter RF pulse produced by an Extended Interaction Oscillator
phase-locks a Coho IF signal. A gunn diode oscillator phase-locked on a
crystal oscillator signal provides the STALO input to the mixers. The

DD FORM 1473 EDITION OF 1 NOV 65 IS OBSOLETE
1 JAN 73

radar is equipped with two separate transmitter and receiver antennae having a 3-foot diameter. The receiver mixer noise figure is 6.5 dB DSB and the transmitter power is 1.2 kw. Pulse width can be adjusted between 0.1 to 2 µs, and Pulse Repetition Rate between 2.5 to 20 KHZ. The radar is now completed and tested. Test results indicate that the Doppler operation is satisfactory and that the minimum range at which the radar can operate is approximately 60 m (400 ns), as primarily limited by the IF amplifier recover time. The Doppler radar is equipped with an on-line signal processor for real-time evaluation of mean Doppler frequency and mean signal intensity.

Accession For	
NTIS GRA&I	☒
DTIC TAB	☐
Unannounced	☐
Justification	
By	
Distribution/	
Availability Codes	
Dist	Avail and/or Special
A-1	

Atmospheric Probing by Active Millimeter Wave System

Final Report

Dr. Roger Lhermitte

March 1985

U. S. Army Research Office
Post Office Box 12211
Research Triangle Park, North Carolina 27709

DAAG 29-82-K-0082

University of Miami
Rosenstiel School of Marine & Atmospheric Science
4600 Rickenbacker Causeway
Miami, Florida 33149

DOD/ARMY Contract No. DAA G29-82-K-0082

FINAL REPORT

ATMOSPHERIC PROBING BY ACTIVE MILLIMETER WAVE SYSTEM

Dr. Roger Lhermitte, Principal Investigator
School of Marine and Atmospheric Science
Division of Meteorology and Physical Oceanography
University of Miami

1. INTRODUCTION.

Doppler radars capable of detecting small hydrometeors such as micron-size cloud droplets can be very useful for the observation of clouds in the early stages of their formation. They can provide information suitable for study of the physics and dynamics which control water condensation and ice phase initiation processes which are at the basis of the formation and evolution of clouds. The approach is to observe radar reflectivity growth and the associated dynamical response in terms of updraft and entrainment arising from latent heat released by condensation and/or freezing processes. Such radars would also be excellent tools for the study of boundary layer wind and turbulence and other intense boundary layer phenomena (dust devils, for instance).

Centimeter wavelength radars with a high power transmitter and a large aperture antenna can be considered for this application, but they lead to bulky equipment which cannot easily be transported. They are also limited in short range operations by the fact that weak target echoes can be overwhelmed by the presence of ground clutter arising from antenna sidelobe effects. The other approach is to use a relatively low power radar operating at the shortest possible wavelength, for which atmospheric attenuation is still acceptable. Such radar operation takes advantage of the λ^{-4} Rayleigh backscattering gain, which applies to small size targets, and also provides a narrow beam with small aperture size antenna. The Rayleigh backscattering gain at 94 GHz is 40 dB with respect to X-band and yet 17 dB with respect to the shortest meteorological radar wavelength (K_a-band, 0.85 cm).

Therefore, the selection of such a very short wavelength radar technique lends itself to low power, small size, highly mobile equipment and is much more immune to ground clutter, thereby allowing monitoring of atmospheric targets at very short range. However, because of the increased signal attenuation by hydrometeors at short wavelength, the observations must be restricted to clouds with no heavy precipitation.

This contract with the Army Research Office called for the development of such a radar system operating at 94 GHz frequency (λ= 3.3 mm) and its use in various atmospheric physics projects. The wavelength was selected because of its location within an acceptable window in the atmospheric absorption spectrum. Also high quality, millimeter wave components for that wavelength have recently become available.

Most of the Contract expenditures were concerned with the purchase of expensive millimiter wave parts. We saved approximately 12,000 on the capital equipment original budget and we believe that the radar parts and the vendors have been selected wisely. This effort and also the basic approach in radar design, led to the assembly of a unique and useful Doppler radar which is described below in more detail. The radar is now completed and has demonstrated satisfactory Doppler operation. At the present time, it is the only 3.3 mm wavelength pulse Doppler radar in existence, devoted to meteorological research. Outside of its interest for cloud physics research, this radar will be available as a test bed for projects related to other uses of millimeter wave radars.

2. GENERAL RADAR DESIGN

The general design of the millimeter wave radar is illustrated by the block diagram in Fig.1, and Figs.2a, 2b and 2c, show photographs of the equipment developed under the ARO contract. The radar operates at a frequency of 93.95 Ghz and includes two identical, rear fed, cassegrain type antennae. Each of the antennae has a 3-foot diameter dish and produces a 0.25°, 3 dB beamwidth, conical beam. One of the antennae is assigned to the receiver, the other to the transmitter. The isolation between the two antennae associated with this configuration exceeds 80 db. This value can be further improved by placing an absorbing panel between the two dishes.

The EIO transmitter tube is attached directly to the back of its antenna, and there is only a short coupler (approximately 4") between the tube waveguide output and the antenna feed input. The coupler is required for sampling the EIO RF pulse to be used in the phase-lock circuits, and is also used occasionally for monitoring transmitter power. The total attenuation introduced by the coupler-waveguide is approximately 1 to 1.5 dB. The receiver assembly composed of the three mixers and the PLO circuits is also attached rigidly to its antenna and the antenna feed is connected to the receiver mixer input through another short coupler.

The antenna-receiver and the antenna-transmitter units, as well as the timing circuits, IF amplifiers, phase detector, etc., are assembled on an aluminium structure which can be tilted to any elevation angle and also rotated in azimuth. The antenna-receiver assembly can be tilted with respect to the aluminium frame, although the transmitter-antenna unit is rigidly attached to it. This provides a means for alignment of the two antenna beams. The entire radar is small and only requires a modest amount of power (600 to 800 watts), so that it can be easily transported and powered in the field.

Firming the final design of the radar and selecting the parts to be purchased required many consultations with other parties, namely: J. Battle, China Lake, California; Varian Associates, Georgetown, Ontario, Canada; Hughes Aircraft, Torrance, California; R. Serafin, National Center for Atmospheric Research, Boulder, Colorado; Pulse Technology, Atlanta, Georgia.

4. TRANSMITTER

A klystron coherent amplifier (Extended Interaction Amplifier, EIA), operating at 94 GHz, has been recently developed by Varian Associates. This device is capable of high gain (40 to 55 dB) coherent amplification at 94 GHz and also delivers substantial power output (1 to 2 kw). Although the EIA coherent amplifier represents a possible solution leading to a very low phase noise and an easy design of the millimeter wave Doppler radar, the prohibitive cost of the tube (75,000)) led us to consider an alternate solution inspired by the less expensive MTI scheme, in which an independent microwave pulse oscillator assisted by a technique for storing the phase of each transmitter pulse is used. This method has been applied widely to centimetric wave Doppler weather radar design and relies on the use of a conventional microwave oscillator, usually a magnetron.

Although a magnetron is commercially available at 94 GHz, this solution was rejected because of the short tube life expectancy and the unknown, but presumably high, intra-pulse FM noise. It was then found that another millimeter wave oscillator, having the same basic structure as the EIA, but much less expensive, was a much more appropriate solution compared to a magnetron, as it provides much better stability characteristics and expected life. This tube is referred to as an EIO (Extended Interaction Oscillator) and is available with a gridded beam-forming structure, so that a low power pulse applied to the grid controls the tube oscillation. The EIO delivers the same power output as the EIA (1 to 2 kw).

The EIO anode voltage is kept constant during the pulse operation, so that there is no need to switch a large amount of power, as is the case with a conventional magnetron. Therefore, very short rise and fall times of a transmitted pulse are easily obtainable, and well-defined square pulses are produced, even for very short pulse operation. The only practical limit as to the shortest pulse possible is the requirement of a matching receiver bandwidth. Since the anode voltage remains steady during the pulse, frequency and power are rapidly established at the pulse start. Therefore, intra-pulse FM noise power is considerably smaller than that associated with the use of a conventional magnetron.

Considerable effort was devoted to the modulator design. This resulted in a transmitter pulse with sharp boundaries and a small amount of phase noise. Tests indeed indicate that the transmitter pulse has a 1.2 kw ±10% peak power and exhibits a 3 ns rise time and a 5 ns fall time (see Fig.3).

The pulse width can be adjusted to selected values between 0.1 and 2 μs and the pulse repetition rate can be adjusted between 2.5 and 20 khz, within the constraint of a maximum duty cycle of $5 \ 10^{-3}$. Note that the minimum 0.1 μs pulse width could be ultimately reduced to 20 ns. This would require increasing the IF frequency to perhaps more than 500 MHz to accommodate the increased bandwidth requirement. This would also provide a range resolution of 3 meters, comparable with that obtained with a laser system.

Tests have shown that the intra-pulse FM noise appears to be considerably smaller than that associated with the use of most magnetrons

at centimeter wavelengths. This excellent performance predicts that, if an EIO is used as the transmitter tube, implementation of the same MTI/COHO technique which has been successfully applied to microwave Doppler radar design, would lead to acceptable results. Tests on the complete radar have indeed confirmed the excellent Doppler operation of the system.

5. RECEIVER

The receiver antenna-feed assembly includes an orthomode transducer which, together with two mixers, can support the simultaneous operation of two separate channels receiving orthogonal polarizations. The local oscillator power source (referred to as Phase Locked Oscillator, PLO) is a gunn diode oscillator phase-locked on 9 GHZ STALO and a 100 MHZ crystal oscillator signal. The mixer-preamplifier double sideband (DSB) noise figure is 6.5 db, which is equivalent to 9.5 dB for single sideband radar operation with no sideband noise rejection, or a noise power of -95 dbm for a 10 MHz bandwidth matching a 200 ns pulse.

A small fraction (-50 dBm) of the transmitted power, derived from a coupler-attenuator assembly, is applied to a third mixer. The mixer's output is used for phase locking of a COHO oscillator which is constrained to start at the same time as the transmitted pulse. Figs.3a,b,c show examples of the downconverted transmitter pulse at the output of this mixer-preamplifier, whose purpose is to phase-lock the Coho. Note the fast pulse rise and fall times (the preamplifier bandwidth is 3 GHZ in this case) and the excellent frequency stability of the signal. Note, however, that in this case, the oscilloscope is triggered by the RF signal, so that Fig.3 does not necessarily indicate phase-lock capability but only repeatability of an RF pulse.

In this preliminary design, the IF (and the COHO) frequency is about 60 MHz for convenience. However, a higher IF frequency is recommended for short pulse operation. Two orthogonal Coho signals are applied to a phase detector together with the IF signal. The phase detector output is the familiar "coherent video" composed of the in-phase, I, and quadrature, Q, signals. Fig. 4 shows examples of one of the coherent video signals with the coho frequency intentionally shifted by approximately 2 MHz with respect to the IF frequency so that the phase-locking process is unambiguously shown. The oscilloscope is now triggered by the same pulse which triggers the EIO modulator (and also the range gate clock) so that any time jitter (for instance affecting the RF pulse initiation) is included in the signals presented in Fig.4. The photograph exposure time is two seconds and the pulse durations are indicated in the figure captions.

This test indicates satisfactory Doppler performance of the radar. The RF phase locking noise is so small that the predominant source of noise may be the Coho signal FM noise. The present Coho signal scheme could be advantageously replaced by a free running crystal oscillator with the phase difference between crystal oscillator and IF pulse being evaluated digitally for each transmitter pulse and injected in the phase demodulator operation.

4. SIGNAL PROCESSING

The two I and Q signals are digitized at 256 or 512 (selectable) range gates spaced by any multiple of 100 ns and the digitized samples are applied to an on-line signal integrator and pulse-pair/autocovariance mean Doppler and spectral variance processor. The processor is conventional except for its ability to operate with closely spaced range gates. This capability requires high speed analog-to-digital converters of the "flash" type and high speed multipliers. Using fast (55 ns) random access memory chips and a pipeline approach for the timing of multiplication and integration steps in the mean Doppler processor leads to an expected minimum spacing between gates of 200 to 300 ns.

In addition to the pulse-pair processor, the signal processing circuits also include non-coherent integration for the evaluation of signal mean intensity. It is planned to process, at each of the 256 or 512 range gates, only the real, $R_1R_2+I_1I_2$, the imaginary, $R_1I_2-R_2I_1$, and the zero lag, $R_1R_1+I_1I_1$, components of signal autocovariance, all expressed in the form of 16-bit samples. The same 16-bit format applies to the additional recording of mean signal intensity at the output of the non-coherent signal integrator, as a fourth sample available at each range gate. The processor includes circuits for the multiplexing and recording of these data.

Both signal processing techniques result in a significant improvement of the receiver sensitivity especially in view of the high pulse repetition rate operation (up to 20kHz) allowed by the radar design. Signal processing for mean signal intensity measurements consists of a non-coherent addition of N_a samples which results in a signal to noise improvement given by $(N_e)^{1/2}$, where N_e is the equivalent number of statistically independent samples. However, the receiver signals at any particular gate are not completely decorrelated because, in a normal Doppler operation, the spectrum width is usually significantly smaller than the Nyquist interval set by the pulse repetition rate. Therefore, N_e is smaller than the actual number of samples, N_a, derived from the repetition rate and the signal dwell-time. The decorrelation time and the ratio N_e/N_a can be derived from $\sigma/2f_n$ where $\pm f_n$ is the Nyquist frequency interval and σ is the Doppler spectrum width. Such computations indicate that for $\sigma/2f_n=0.1$, for instance, the ratio $N_e/N_a=0.3$. They also show that, at a PRF of 20 KHz and 94 GHz radar frequency (Nyquist frequency interval ±16 m/s) and a plausible Doppler spectral width of $\sigma_v=2ms^{-1}$, 10,000 independent samples will be acquired in a 2 second signal dwell time. This is equivalent to a 20 dB signal to noise improvement.

The evaluation of the additional signal-to-noise improvement associated with coherent mean Doppler processing depends on the coherent signal bandwidth compared with the Nyquist interval set by the pulse repetition rate. With the same example as discussed above, ($\sigma/2f_n=0.1$), and using an efficient estimator such as the pulse-pair algorithm which we have implemented, the s/n improvement is expected to reach more than 30 dB for a 2-second signal dwell time.

Such estimates will be investigated by comparing the improvement of detection threshold for actual data, resulting from the use of both mean

signal intensity and mean Doppler frequency for a variety of signal dwell times. Since both mean intensity and mean Doppler processing techniques rely on linear addition of samples, such investigations can be pursued by integrating shorter term samples in a computer program.

6. SYSTEM PERFORMANCE

With the present 60 MHz IF frequency, the minimum time delay at which backscattering can be observed is approximately 400 ns after the transmitter pulse trailing edge. However, this performance can be improved by upgrading the system to a higher IF frequency, which is planned to be done in the near future. It is also expected that this millimeter wave radar is much less sensitive to echoes produced by ground targets "seen" through antenna sidelobes, so that the importance of ground clutter should be drastically reduced thereby allowing the operation of the radar at short range.

The sensitivity of the radar is evaluated from the conventional radar equation:

$$10\log\eta = 10\log P_r - 10\log P_t + 10\log 4\pi R^2 - 10\log h - 10\log A_e$$

P_r is the received signal, P_t is the transmitted peak power, $h=\tau c/2$ is the pulse length, A_e is the effective area of the receiving antenna (which includes a 0.6 antenna efficiency factor), R is the distance of the target and η is the target reflectivity.

Inserting our radar characteristics and with h=60m, we have:

$$10 \log\eta = dbm -25 + 20 \log R$$

where η is in cm^{-1}, dbm is the received signal intensity expressed in dB below a milliwatt, and R is the target range in kilometer. This equation includes a 0.6 efficiency factor for the antenna, but does not include any other signal attenuation effects occurring either in the equipment or in the atmosphere.

The receiver noise figure is 6.5 db DSB and the peak power is slightly over 1 kw. In these conditions, and assuming a $\tau=400$ ns pulse (5 MHz receiver bandwidth), the radar reflectivity at a range of one kilometer for which signal=noise, (including 1.5 dB losses between transmitter and receiver and its particular antenna), is estimated to be approximately $5*10^{-13}$ cm^{-1}. As a reference, Fig. 5 shows 94 GHZ reflectivity values calculated, for cloud droplets within the Rayleigh domain, using a conveniently simple monodisperse size distribution. The results are shown as a function of droplets' size and for several values of cloud liquid water.

The above estimate of radar sensitivity includes an antenna efficiency factor of 0.6, but does not take into account the loss of sensitivity associated with partial merging of the transmitter and receiver beams at short range. However, the antenna geometry in terms of the separation and

slight convergence of the two beams indicates that this effect is only significant below a range of 300 meters. Also, the above equation does not include attenuation by atmospheric water vapor which can reach 2 to 3 db (one-way) for tropical climate such as the summer weather in South Florida.

7. CONCLUSION AND PLANS

Preliminary tests of the millimeter wave Doppler radar have been completed and have demonstrated satisfactory Doppler operation. The system will be operated for cloud observations in a vertically pointing mode very shortly.

The assembling of the radar for testing was done using a rudimentary pedestal sufficient for the testing of the radar which must be improved for field use of the equipment.

There are certain engineering changes which would improve the radar operation. The IF frequency should be increased to perhaps more than 160 MHz for better handling of some of the bandwidth requirements. Also, we have experienced frequency drifts of a few MHz resulting from tube warming. Changing the pulse duty cycle produces the same effect, as this action modifies the load conditions of the modulator power supply. We are currently compensating for these frequency drifts by mechanical adjustment of the EIO frequency using the phase detector output as a guide. However, unattended use of the radar will require automatic adjustment of the drift. This can be done with relative ease by controlling either the EIO anode voltage or the PLO frequency. As mentioned above, the Coho scheme should also be replaced by a fixed frequency crystal oscillator to remove possible contribution of the Coho FM noise. The frequency difference between the crystal frequency and the IF frequency during the transmitter pulse time could be used as an input to the transmitter tube -or PLO- frequency control circuits. These engineering improvements, which are relatively easy to implement, would make the system acceptable for automatic operation. Also, the radar range resolution (45 meters now in the Doppler mode, can be improved later).

The radar system will also be calibrated so that it can be used for quantitative measurements of target radar cross section and reflectivity. Since we do not have a calibrated signal generator operating at 94 GHZ, we are planning to use the sun as a radiation source for calibration purposes.

8. PUBLICATIONS

Lhermitte, R. and C. Frush, 1984, Millimeter Wave Radar for Meteorological Observations, Preprints, 22[d] Radar Meteorology Conference, Amer. Meteorcl. Soc., Zurich, Switzerland.

9. MEETINGS ATTENDED

22[d] Radar Meteorology Conference, Amer. Metor. Soc., Sept. 1984, Zurich, Switzerland.
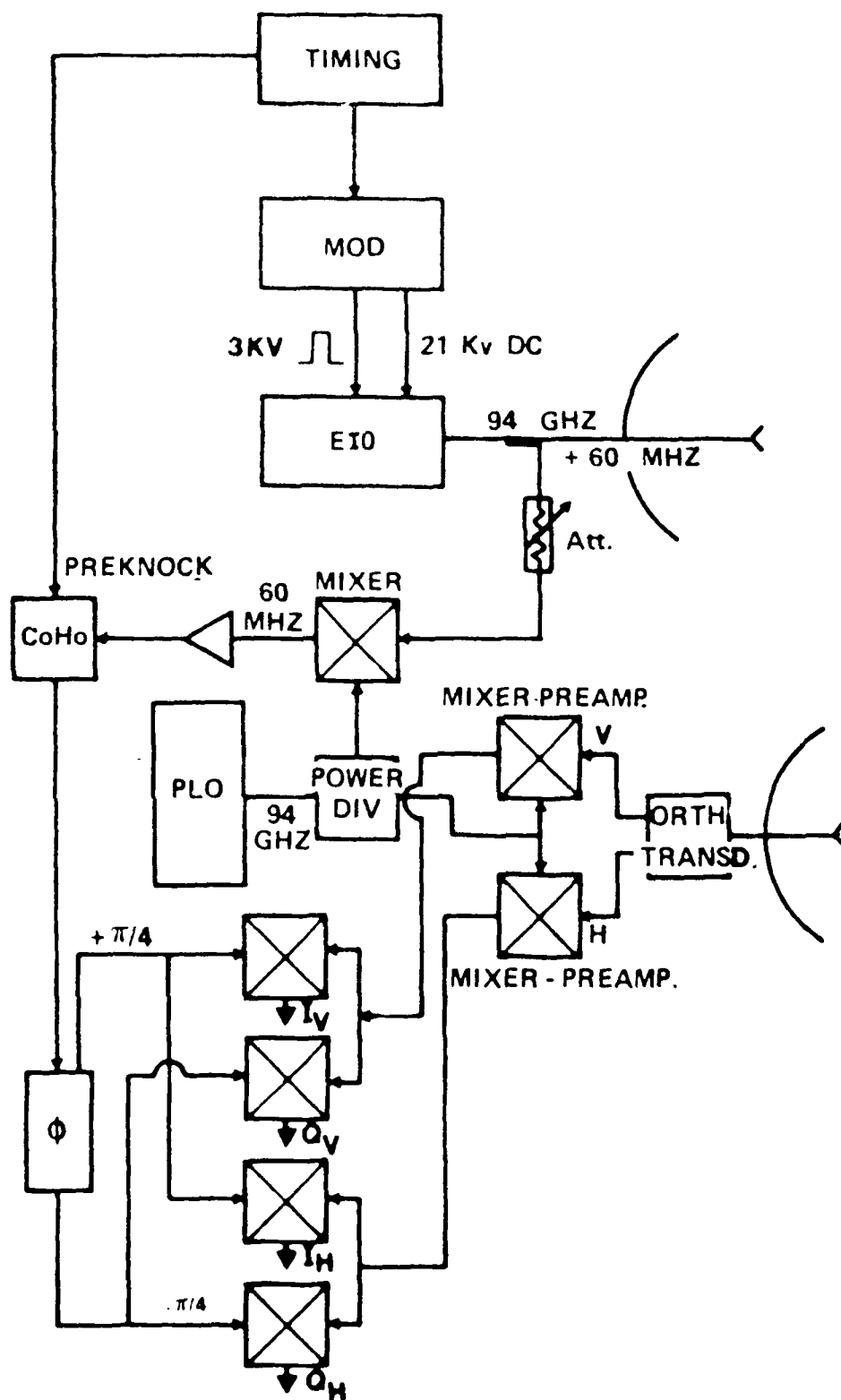
Fig.1 Radar Block Diagram.
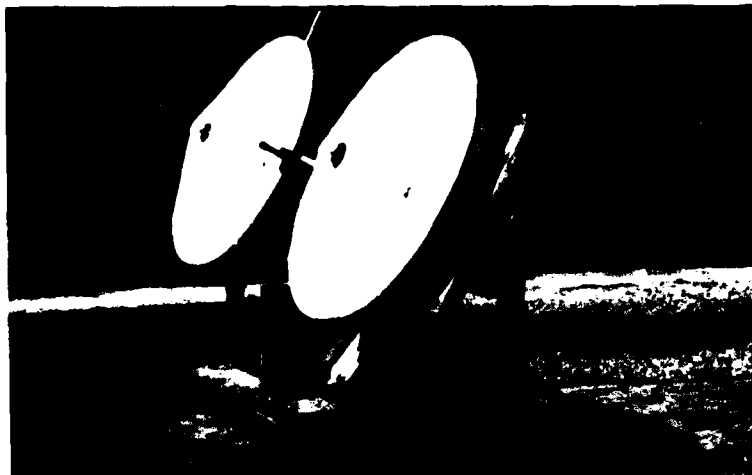
Fig. 2a. Front view of the radar assembly
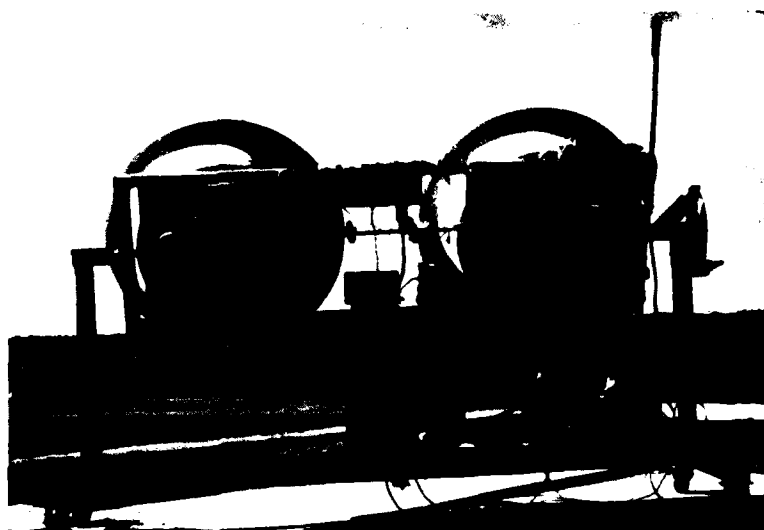
Fig. 2b. Rear view of the radar assembly
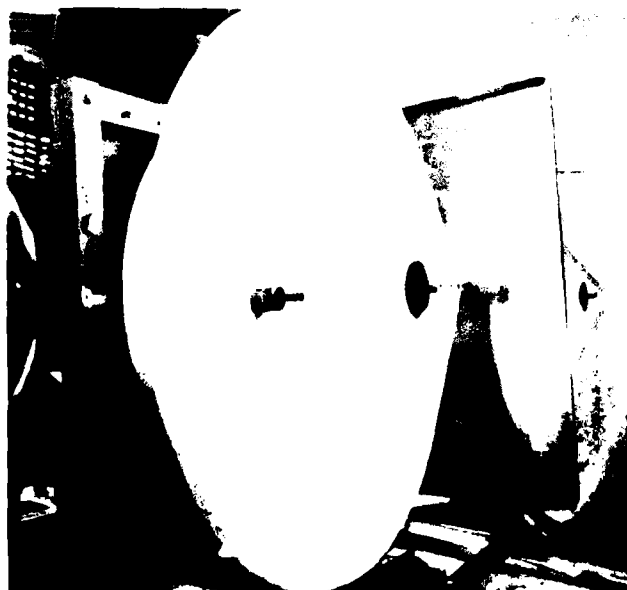
Fig.2c. One of the Cassegrain antenna
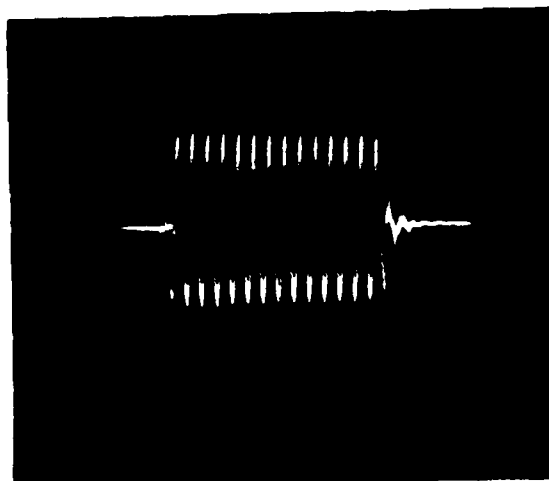
Fig.3a IF signal at the output of one of the mixer-preamplifiers which are part of the receiver. Mixer inputs are EIO pulse and PLO signal. Pulse width 0.3µs, IF frequency 55 MHZ.
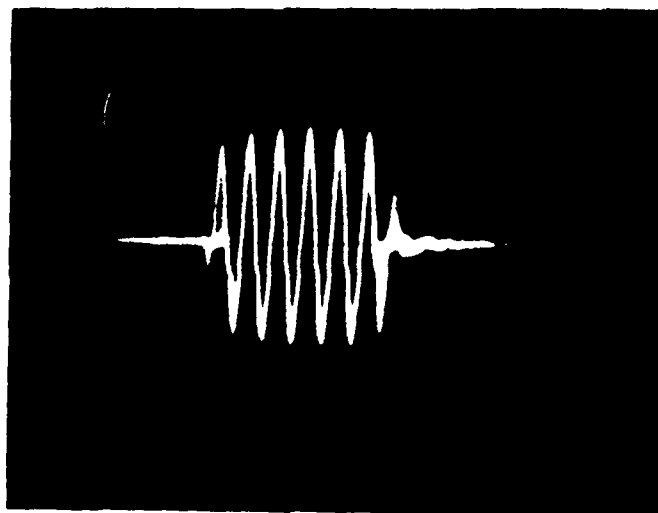
Fig. 3b. Same as Fig. 3a but 0.1 µs pulse width. IF frequency 55 MHZ.
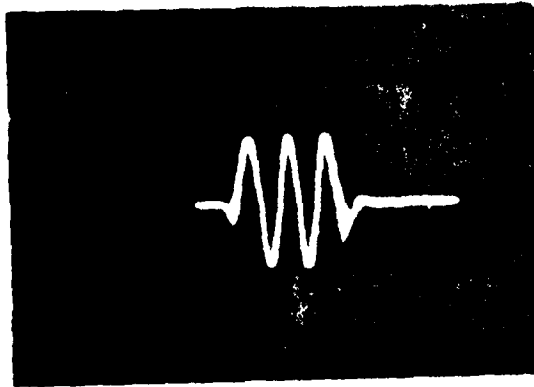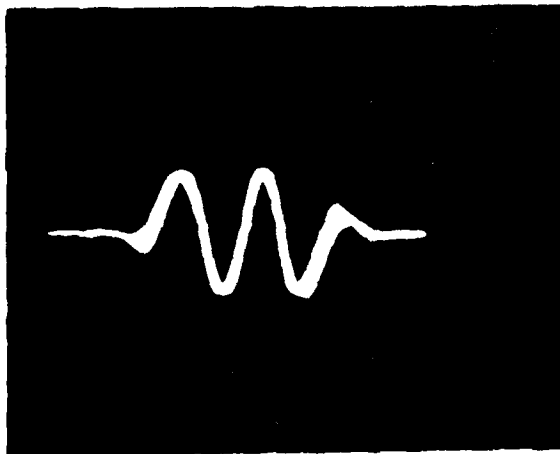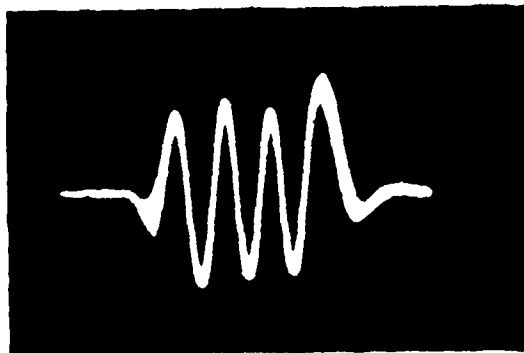
Fig. 4 Coherent video signal at the output of the
phase demodulator. PRF 10 KHZ. Exposure time 2 seconds.

a. Pulse width 1.5μs,   Coho/IF frequency offset 2 MHZ
b. Pulse width 1μs,   Coho/IF frequency offset 3 MHZ
c. Pulse width 1μs,   Coho/IF frequency offset 5.8 MHZ.
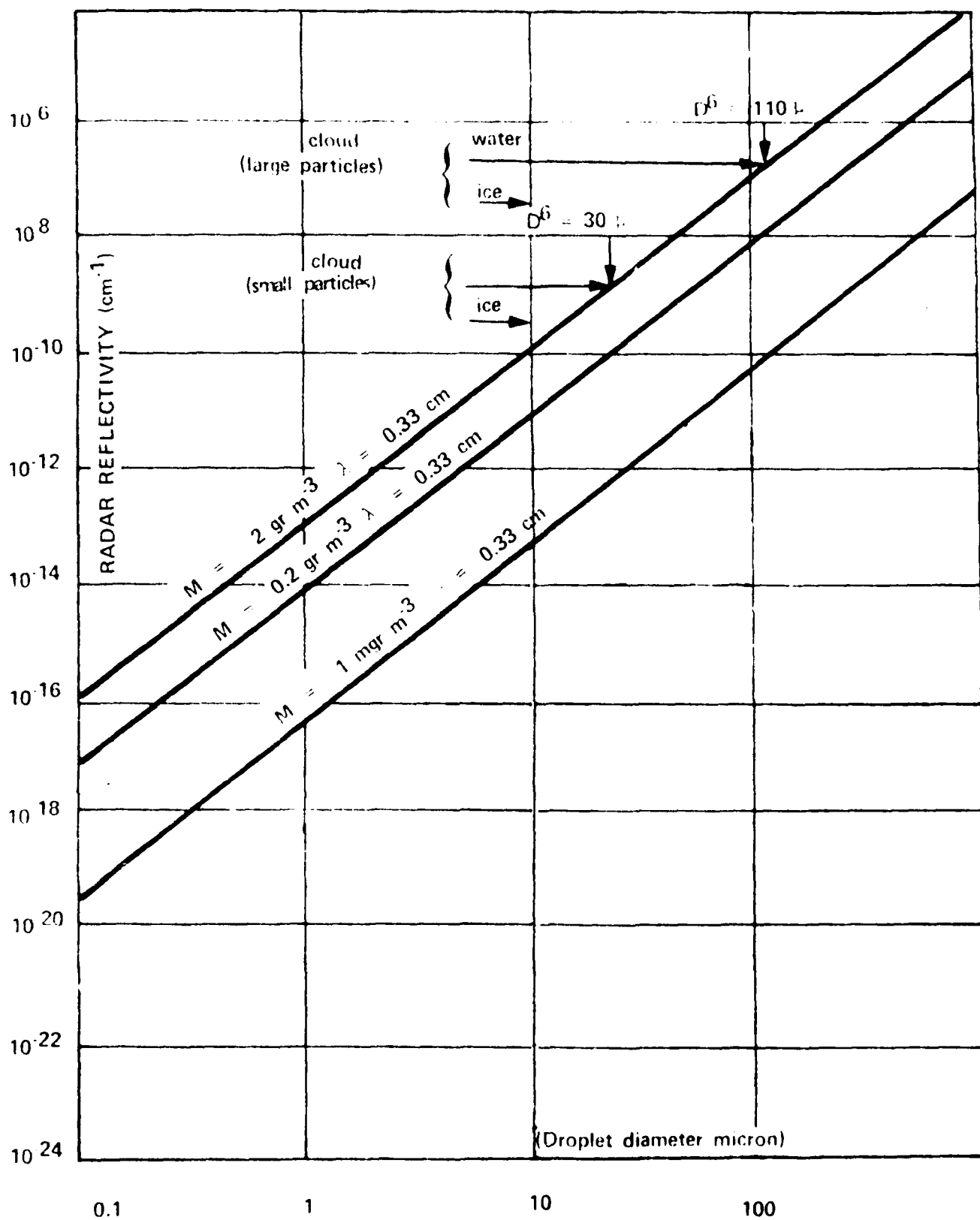
Fig. 5. Radar reflectivity at 94 GHZ evaluated assuming a
cloud composed of droplets of the same size, as a function
of that size and for the cloud liquid water indicated.

8.1

MILLIMETER WAVE RADAR FOR METEOROLOGICAL OBSERVATIONS.

Roger Lhermitte
University of Miami , Miami, Fla.

Charles Frush
National Center for Atmospheric Research*, Boulder, Colorado.

1. INTRODUCTION.

Doppler radars capable of detecting small hydrometeors such as micron-size cloud droplets can be very useful for the observation of clouds in the early stages of their formation. They can provide information suitable for study of the physics and dynamics which control water condensation and ice phase initiation processes which are at the basis of the formation and evolution of clouds. The approach is to observe radar reflectivity growth and the associated dynamical response in terms of updraft and entrainment arising from the latent heat released by the condensation and/or freezing process. Such radars would be also excellent tools for the study of boundary layer wind and turbulence and other intense boundary layer phenomena (dust devils, for instance).

There are two ways to achieve detection of small cloud particles as well as the high space resolution needed for such radar application:
a. Centimeter wavelength radars with high power transmitter and large aperture antenna.
b. Relatively low power radars operating at the shortest wavelength possible, which take advantage of the λ^{-4} Rayleigh backscattering gain and provide a narrow beam with small aperture size antenna.

The first solution leads to bulky equipment which cannot be easily transported and is also limited in short range operation by the fact that weak target echoes can be easily overwhelmed by the presence of ground clutter arising from conventional antenna sidelobe effects. The second solution lends itself to low power, small size, highly mobile equipment and is much more immune to ground clutter, thereby allowing very short range monitoring of atmospheric targets. However, because of the increased signal attenuation at short wavelength, the observations must be restricted to clouds with no heavy precipitation.

The short wavelength, low power radar solution was selected for use in a cloud physics research effort and this paper presents the millimeter wave Doppler which was designed and assembled for this project.

2. CHOICE OF WAVELENGTH.

The shortest meteorological radar wavelength for which substantial hardware was available in the past was the "K_a" band centered on approximately 0.86 cm in an atmospheric propagation window.

However, relatively low cost, high quality, millimeter wave components designed for operation at a higher frequency (W-band, 94 GHz, or $\lambda=3.3$ mm) have recently become available. Since this frequency band is located inside another atmospheric propagation window, these new developments offer an opportunity to extend the shortest meteorological radar wavelength to a value which would provide a further significant increase of the Rayleigh backscattering gain (40 dB with respect to X-band and yet 17 dB with respect to K_a-band).

A klystron coherent amplifier (Extended Interaction Amplifier, EIA) is among the newly developed components. This device is capable of high gain coherent amplification at 94 GHz and also delivers a substantial power output (1 to 2 kw). Although the EIA coherent amplifier solution represents an optimum choice for the design of a millimeter wave Doppler radar, the prohibitive cost of the tube led us to consider an alternate solution inspired from the less expensive MTI scheme. This method is widely used in Doppler weather radar design and relies on the use of a conventional microwave oscillator, usually a magnetron. Although millimeter wave magnetrons are available, they were rejected because of the short tube life expectancy and the unknown, but presumably high, intra-pulse FM noise. It was then found that another millimeter wave oscillator using the same basic structure as the EIA, but less expensive, was a much more appropriate solution regarding frequency stability characteristics and expected life. This tube is referred to as an EIO (Extended Interaction Oscillator) and is available with a gridded beam-forming structure, so that a low power pulse applied to the grid controls the tube oscillation. The EIO delivers the same power output as the EIA (1 to 2 kw). Since the anode voltage is kept constant during the pulse operation, the device has the following advantages:

There is no need for switching a large amount of power as is the case for a conventional magnetron, for instance. Therefore, very short rise and fall times of the transmitted pulse are easily obtainable, thereby producing a well-defined square pulse even for very short pulse operation. The only practical limit as to the shortest pulse possible is the requirement of a matching receiver bandwidth. Since the anode voltage remains steady during the pulse, frequency and power are rapidly established at the pulse start. Therefore, intra-pulse FM noise is considerably smaller than that associated with the use of a conventional magnetron.

At the time of this writing a Doppler radar using a 94GHz EIO has been assembled and

preliminary tests have been performed. This paper describes the system and shows the results of the first tests.

3. GENERAL RADAR DESIGN.

The general design of the millimeter wave radar is illustrated by the block diagram in Fig.1, and Fig.2 shows a photograph of the equipment. The radar operates at a frequency of 93.95 Ghz and includes two identical, rear fed, cassegrain type antennae. Each of the antennae has a 3-foot diameter dish and produces a beam with 0.2°, 3 dB beamwidth. One of the antennae is assigned to the receiver, the other to the transmitter. The isolation between the two antennae associated with this configuration exceeds 80 db. This value can be further improved by placing an absorbing panel between the two dishes.

Both the transmitter and the entire receiver unit are attached directly to the back of their respective antenna, thereby minimizing waveguide losses which are an important consideration at the short operating wavelength. Although the receiver components are rigidly attached to the back of the antenna dish, the whole antenna-receiver assembly can be tilted for the purpose of alignment of the two antenna beams. The entire radar has a small size and only requires a modest amount of power (600 to 800

Fig.2 Photograph of the rear of the radar showing the transmitter to the left and the receiver to the right. The size of each of the antennae is 3 feet.

watts), so that it can be easily transported and powered in the field. These characteristics are particularly advantageous for possible application of the system to airborne operation.

4. TRANSMITTER.

Considerable effort was devoted to the modulator design. This resulted in a transmitter pulse with sharp boundaries and a small amount of phase noise. Tests indeed indicate that the transmitter pulse has a 1.2 kw peak power and exhibits a 3 ns rise time and a 5 ns fall time. Recall that 5 ns is equivalent to a radar range of less than a meter!

The pulse width can be adjusted to selected values between 0.1 and 2 μs and the pulse repetition rate can be adjusted between 2.5 and 20 khz. Note that the minimum 0.1 μs pulse width could be ultimately reduced to 20 ns. This would require increasing the IF frequency to perhaps more than 500 MHz to accomodate the increased bandwidth requirement. This would also provide a range resolution of 3 meters, comparable with that obtained with a laser system.

The intra-pulse FM noise appears to be substantially smaller than that associated with the use of most magnetrons at centimeter wavelengths. This excellent performance predicts that the implementation of a MTI/COHO technique, which has been successfully applied to microwave Doppler radar design, would lead to acceptable results if an EIO is used as the transmitter tube.

5. RECEIVER.

The receiver antenna feed assembly includes an orthomode transducer which, together with two mixers, supports the simultaneous operation of two separate channels receiving orthogonal polarizations. The local oscillator power source (referred to as Phase Locked Oscillator, PLO) is provided by a phase locked gunn diode oscillator which derives its coherence from both a 9 GHz stalo and a highly stable 100 mhZ reference. The mixer-preamplifier noise figure is 6.5 db (double sideband) which is equivalent to 9.5 dB for radar operation with no sideband rejection, or a noise power of -95 dbm for a 10 MHz bandwidth matching a 200 ns pulse.

Fig.1 Radar Block Diagram.

A small fraction of the transmitted power is applied to a third mixer. The mixer's output is used for phase locking of a COHO oscillator which is constrained to start at the same time as the transmitted pulse. Fig.3 shows the downconverted transmitter pulse at the output of this mixer-preamplifier. Note the fast pulse rise and fall times and the excellent frequency stability of the signal. Note, however, that in this case, the oscilloscope is triggered by the RF signal, so that Fig.3 does not necessarily indicate phase lock capability but only repeatability of the RF pulse.

In this preliminary design, the IF (and the COHO) frequency is 60 MHz for convenience. However, a higher IF frequency is recommended for short pulse operation. The coho output is applied to a conventional phase detector. The output is the coherent video composed of the familiar in-phase, I, and quadrature, Q, signals. Fig. 4 shows examples of the coherent video signals with the coho frequency intentionally shifted by approximately 2 MHz with respect to the IF frequency so that the phase locking process is unambiguously shown. The oscilloscope is now triggered by the same pulse which triggers the EIO modulator (and also the range gate clock) so that any time jitter (for instance affecting the RF pulse initiation) is included in the signals presented in Fig.4. The photograph exposure time is two seconds and the pulse durations are indicated in the figure captions.

This test indicates that the RF phase locking noise is so small that the predominant source of noise may be the Coho signal FM noise. Therefore, the present coho signal scheme could be advantageously replaced by a free running crystal oscillator with the phase difference between crystal oscillator and IF pulse being evaluated digitally for each transmitter pulse and compensated for in the phase demodulator operation.

The two I and Q signals are digitized at 256 or 512 (selectable) range gates spaced by any multiple of 100 ns and the digitized samples are applied to an on-line signal integrator and pulse-pair processor. The processor is conventional except for its ability to operate with closely spaced range gates. This capability requires high speed analog-to-digital converters of the "flash" type and high speed multipliers. Using a pipeline approach for the timing of multiplication and integration steps in the mean Doppler processor leads to an expected design goal of less than 200 ns between gates. The processor includes circuits for the recording of the data.

With the present 60 MHz IF frequency, the minimum time delay at which backscattering can be observed is approximately 400 ns after the transmitter pulse trailing edge. However, this performance can be improved by upgrading the system to a higher IF frequency, which is planned to be done in the near future.

6. SYSTEM PERFORMANCE.

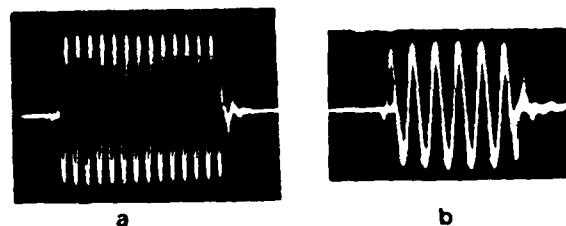The sensitivity of the radar is evaluated from the conventional radar equation:

Fig.3 IF signal at the output of the phase lock mixer. IF frequency is approximately 50 MHz. Time exposure is 2 seconds. a. 300 ns pulse . b. 100 ns pulse. Note that the signal noise in the begining and the end of the pulse does not exceed 10 ns.
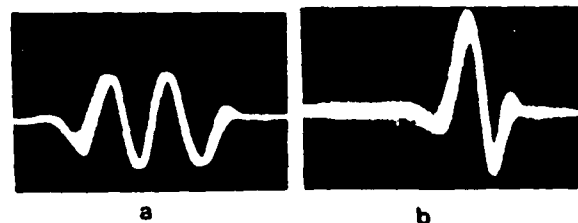
Fig.4 Coherent video signal during the transmitter pulse. a. 1 microsecond pulse. b. 300 ns pulse. Coho frequency offset is approximately 2 MHz.

$$10\log\eta = 10\log P_r - 10\log P_t + 10\log 4\pi R^2 - 10\log h - 10\log A_e$$

P_r is the received signal, P_t is the transmitted peak power, $h=\tau c/2$ is the pulse length, A_e is the effective area of each of the two antennae (which must include the antenna efficiency factor), R is the distance of the target and η is the target reflectivity.

The receiver noise figure is 6.5 db DSB and the peak power is slightly over 1 kw. In these conditions, and assuming a $\tau=400$ ns pulse (5 MHz receiver bandwidth), the radar reflectivity at a range of one kilometer for which signal=noise, (including 1.5 dB losses between transmitter and receiver and its particular antenna), is estimated to be approximately 10^{-13} cm^{-1}. This estimate includes an antenna efficiency factor of 0.6, but does not take into account the loss of sensitivity associated with partial merging of the transmitter and receiver beams at short range. However, the antenna geometry in terms of the separation and slight convergence of the two beams indicates that this effect is only significant below a range of 300 meters. Note that it is expected that this millimeter wave radar is more immune to ground clutter than longer wavelength radars and will therefore be able to operate at very short ranges.

7. SIGNAL PROCESSING.

The processing of the radar signals includes non-coherent integration for the evaluation of signal mean intensity and also coherent integration using a pulse-pair/autocovariance algorithm. Both techniques result in a significant improvement of the receiver

sensitivity especially in view of the high pulse repetition rate operation (up to 20kHz) allowed by the radar design.

The signal processing for mean signal intensity measurements consists of a non-coherent addition of N_a samples which results in a signal to noise improvement given by $(N_e)^{1/2}$, where N_e is the equivalent number of statistically independent samples. However, the receiver signals at any particular gate are not completely decorrelated because, in a normal Doppler operation, the spectrum width is usually less than the Nyquist interval set by the pulse repetition rate. Therefore, N_e is smaller than the actual number of samples, N_a, derived from the repetition rate and the signal dwell-time. The decorrelation time and the ratio N_e/N_a can be derived from $\sigma/2f_n$ where $\pm f_n$ is the Nyquist frequency interval and σ is the Doppler spectrum width. Such computations indicate that for $\sigma/2f_n=0.1$, the ratio $N_e/N_a=0.3$. At a PRF of 20 kHz and a 94 GHz radar frequency, the Nyquist frequency interval is ±16 m/s so that with a plausible Doppler spectral width of $\sigma_v=2ms^{-1}$, 10,000 independent samples will be acquired in a 2 second signal dwell time. This is equivalent to a 20 dB signal to noise improvement.

The evaluation of the additional signal-to-noise improvement associated with mean Doppler processing depends on the coherent signal bandwidth compared with the PRF Nyquist interval set by the pulse repetition rate. With the same example as discussed above, the ratio of bandwidth to Nyquist frequency interval is 10. Using an efficient estimator, such as the pulse-pair algorithm which we have implemented, the s/n improvement is expected to reach more than 30 dB for a 2-second signal dwell time.

Such estimates are very conservative and will be investigated by comparing the improvement of detection threshold for actual data, resulting from the use of both mean signal intensity and mean Doppler frequency for a variety of signal dwell times. Since both mean intensity and mean Doppler processing are based on linear addition of samples, such investigations can be pursued by processing short term mean samples in a computer program. Anyhow, even a 20db s/n improvement will bring the minimum detectable reflectivity for targets at a range of 1 km, to less than 10^{-15} cm^{-1}. This is the value calculated for a cloud with 1 mg/m^3 water content and composed of a monodisperse distribution of 2 μ diameter liquid droplets!

8. CONCLUSION.

Preliminary tests of the millimeter wave Doppler radar have been completed and have shown that a satisfactory Doppler operation is possible. The system will be operated for cloud observations in a vertically pointing mode very shortly.

We intend to enclose the entire radar in a 8×4×4 foot box with a mylar window in front of the antenna. This will provide a convenient solution for an all-weather operation of the system either in a fixed vertically pointing mode (on the top of a van for instance), or in a

scanning mode by attaching the box to a radar pedestal.

There are certain number of engineering improvements which are needed. The IF frequency should be increased to perhaps much more than 160 MHz for better handling of some of the bandwidth requirements. Also, we have experienced frequency drifts of a few MHz resulting from tube warming. Changing the pulse duty cycle produces the same effect, as this action modifies the load conditions of the modulator power supply. We are currently compensating for these frequency drifts by mechanical adjustment of the EIO frequency using the phase detector output as a guide. However, unattended use of the radar such as in an airborne configuration, will require automatic adjustment of the drift. This can be done relatively easily by controlling either the EIO anode voltage or the PLO frequency. As mentioned above, the coho scheme should also be replaced by a fixed frequency crystal oscillator to remove possible contribution of the coho FM noise. The frequency difference between the crystal frequency and the IF frequency during the transmitter pulse time could be used as input to the transmitter tube -or PLO- frequency control circuits. These engineering improvements, which are relatively easy to implement, would make the system acceptable for automatic operation aboard an airplane or perhaps a satellite.

The radar system will also be calibrated so that it can be used for quantitative measurements of target radar cross section and reflectivity. Simultaneous operation of both horizontal and vertical polarizations in the receiver system will be allowed.

The radar range resolution -(15 meters now, can be improved later)- together with the use of narrow beams (0.2°), the excellent sensitivity of the radar (10^{-14} cm^{-1} at 1 km and no signal integration), should allow observation of light clouds with comfortable signal-to-noise performance and high space resolution. This performance of the radar including dual polarization and Doppler capabilities will make it an attractive tool for cloud physics research.

Acknowledgements.

END

FILMED

6-85

DTIC